

Accelerometer-Assisted Tracking and Pointing for Deep Space Optical Communications: Concept, Analysis, and Implementations

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Abstract—NASA/JPL has been developing technologies for deep space tracking and pointing of an optical communication beam using linear accelerometers. Linear accelerometers provide excellent accuracy in sensing the vehicle's acceleration with an advantage of small size, low cost, and a broad range of well developed products.

Accurate and stable pointing is the most critical function necessary to establish a successful free-space optical communication link. Generally known as the line of sight problem, it is also common to image stabilization. The most dominant mis-pointing error source is the spacecraft vibration that causes line-of-sight jitter during beam pointing. Line of sight stabilization using the detection of spacecraft vibration has been previously pursued with gyros, angle sensors, and more recently, angular rate sensors.

The goal of this research is to achieve sub-microradian pointing for deep space optical communications. The most critical tracking parameter to achieve sub-microradian pointing under the spacecraft vibration is the tracking update rate. The degree of suppression of spacecraft vibration is proportional to the tracking rate. Current tracking system relies on optical beacon sources such as ground based laser beacon, extended sources (such as Sun-illuminated Earth or Moon), and stars. However, for deep space ranges, the intensity of these beacon sources is not sufficient to support the required tracking rate that is often few kHz. However, the tracking rate can be effectively increased by employing inertial sensors, which can command the pointing mechanism to compensate for the spacecraft vibrations.

In this paper, we will present the concept of accelerometer-assisted tracking, error analysis, and progress made on its implementations.

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1. INTRODUCTION

Accurate tracking of a ground receiver location and the pointing of downlink laser beam are critical functions required for the success of any free-space optical communications. This function has been known, in general, as the line of sight (LOS) stabilization to both space-based camera and optical pointing systems. For the future deep space optical communications, the pointing requirements are very stringent and in the range of sub-microradians¹. Because of the tight pointing requirements, major sources of mis-pointing need to be minimized. The most dominant mis-pointing source for deep space optical communications is the spacecraft (S/C) vibration caused by thrusters and other onboard instruments such as gyros and reaction wheels. Accurate pointing under S/C vibration requires fast commanding on pointing mechanism (Fine Steering Mirror) which precedes fast tracking of the receiver location. One popular S/C vibration model after the measured vibration spectrum of Olympus S/C indicates that vibration spectrum up to few hundred Hz needs to be measured to effectively reduce the pointing error. It has been reported that substantial reduction of pointing error can be achieved by using a focal plane array (FPA) capable of tracking at several kHz^{2,3,4}. Currently, a typical method is to locate a receiver position through the detection of laser beacon source on FPA such as a CCD. The location of the beacon and the transmit laser on the FPA can be directly translated into a pointing command to the fine steering mirror. Potential beacon sources include an uplink laser, extended sources such as Earth and Moon, and stars. The common drawback of these beacon sources, however, is that the light intensity is not usually sufficient to support the desired high tracking rate. Since the need for high tracking rate comes from the fact that the S/C vibration causes the motion of the beacon on FPA, the fast tracking of S/C position relative to the beacon position would substitute the fast tracking of beacon. Therefore, high frequency spacecraft vibrations can

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In this paper, we present the feasibility a linear accelerometer for tracking and pointing system of optical communications through analysis and experimental results. The advantages of accelerometers include its small size, low mass, power, cost, broad range of well developed linear accelerometer technologies and the excellent performance demonstrated in recent flight missions.^{6,7} The challenges is to accurately estimate the angular positions of S/C from the measurements of S/C vibrations.

The architecture of the proposed tracking and pointing subsystem employs two tracking loops, one for low frequency measurements through optical tracking and high frequency measurements through inertial tracking. This architecture is depicted in Figure 1.

A pair of parallel mounted accelerometers A_1 and A_2 are shown in Figure 2. The angle, θ , can be estimated from the individual readings of accelerometers, A_1 and A_2 , after converting the accelerations into linear displacements, d_1 and d_2 with the small angle assumption.

The diagram illustrates a closed-loop tracking system, divided into a **Slow Tracking Loop** and a **Fast tracking loop**.

Slow Tracking Loop:

- A **Beacon** (represented by a starburst) emits a signal received by the **Rx FPA** (Receiver Front-End).
- The **Rx FPA** outputs to a block labeled **correction using accel. measurement**.
- This block outputs to a summing junction (+).
- The **Tx FPA** (Transmitter Front-End) receives input from the summing junction and outputs to a **Mirror Driver**.
- The **Mirror Driver** controls a mirror that reflects the **Tx Laser** beam.
- The **Compen. Filter** (Compensation Filter) receives input from the **Fast tracking loop** and outputs to the **Mirror Driver**.
- The **Fast tracking loop** also receives input from the **Point Ahead** signal.

Fast tracking loop:

- Input: **S/C Vibration** (represented by a waveform).
- Block: **Accelerometer**.
- Block: **A/D Converter**.
- Block: **Position estimates**.
- Block: **LPF** (Low Pass Filter).
- Summing junction (+) combining inputs from the **Point Ahead** signal and the **LPF**.
- Output: The summing junction output feeds into the **Compen. Filter** and the **Fast tracking loop**.

In order to use linear accelerometer pairs to measure angular displacements, either software or hardware implementation

Since l , the separation, is a known measurable constant, θ is determined with the precision of A_1 and A_2 . Angular

displacements on two axis (α , β) can be obtained using three accelerometers as shown in Figure 3. Three accelerometers are placed on the y-z plane. Assume acceleration is in x-direction, then displacement estimation using accelerations from B and C gives an angular displacement (α) on x-y plane. Using A and the mean of B and C gives an angular displacement (β) on the x-z plane.

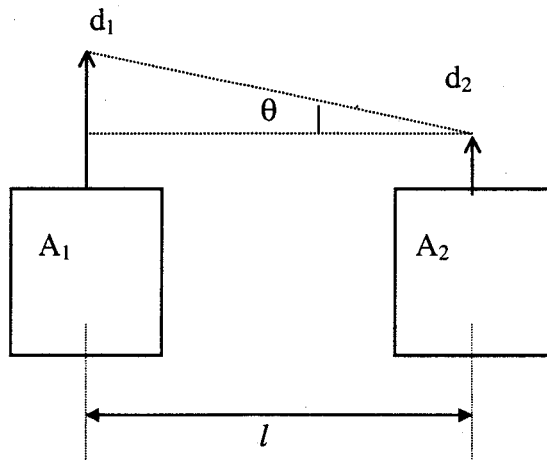


Figure 2. A pair of linear accelerometer arranged to estimate an angular displacement

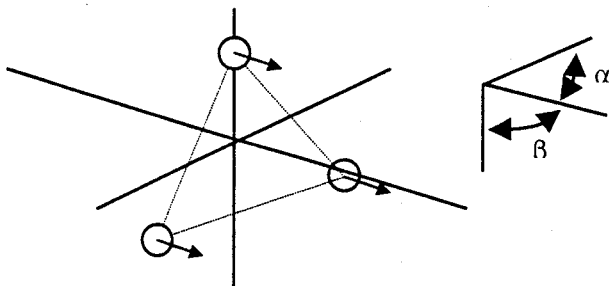


Figure 3. Triangular configuration of three accelerometers to estimate two axis angular displacements

3. REQUIREMENT ON ACCELEROMETER ACCURACY

There are two types of errors caused by the accelerometer that affect displacement estimation errors: accelerometer electronic noise and frequency response error. Electronic noise is the wide bandwidth random noise such as white noise. Electronic noise is the primary error factor for displacement estimation while the frequency response error is the static error that is a function of frequency. The frequency response error is rather small and calibration can reduce it down to 0.5% for AlliedSignal QA3000 accelerometers. Therefore, we will focus on electronic noise for performance estimation hereafter. In order to estimate

the displacement error from accelerometer noise, a displacement estimation equation in terms of acceleration needs to be derived. This has been reported in [12] and summarized in equation (1).

$$p_N = \sum_{i=2}^{N-1} (N-i)a_i \Delta t^2 + (N/2-2/3)a_1 \Delta t^2 + a_N \Delta t^2 / 6 + (N-1)v_1 \Delta t + p_1 \quad (2)$$

where

p_N : linear displacement at sampling time of N
 a_N : acceleration measurement at sampling time of N
 v_1 : initial velocity
 p_1 : initial position
 N : number of acceleration measurements

The corresponding position estimation error can be expressed as a function of the acceleration measurements noise (1 sigma value), σ_a , assuming the a_i 's are iid (independent, identically distributed) random variables.¹²

$$\sigma_{pN} = \Delta t^2 \sigma_a \left(\sum_{i=2}^{N-1} (N-i)^2 + (N/2-2/3)^2 + 1/36 \right)^{1/2} \quad (3)$$

An angular position estimation error can be derived from Eq.(1) assuming the two linear position estimates, d_1 and d_2 are iid random variables with its rms error of σ_{pN} in Eq.(3).

$$\begin{aligned} \sigma_{\theta N}^2 &= (\text{Var}(d_1) + \text{Var}(d_2)) / l^2 \\ &= 2 \sigma_{pN}^2 / l^2 \end{aligned}$$

$$\text{or} \quad \sigma_{\theta N} = \sqrt{2} \sigma_{pN} / l \quad (4)$$

The position estimation error (1 sigma value) using QA-3000 accelerometer noise of $76\mu\text{g}$ (10~500Hz) and sampling rates of 2kHz and 5kHz are plotted in Figure 4 for an integration period up to 100msec assuming accelerometer separation of 30cm. From this plot, requirement on accelerometer noise can be deduced. For sub-microradian pointing, angular displacement estimation error should not exceed $0.16\mu\text{rad}$ if we take previous mission studies such as Europa mission study where $0.071\mu\text{rad}$ was allocated to the displacement estimation error given the total rms tracking error of $0.45\mu\text{rad}$ ¹. This translates to linear displacement error of $0.034\mu\text{m}$ that corresponds to the maximum integration period of 0.03second or optical tracking rate of 33Hz for 5kHz sampling. Since the angular displacement error is directly proportional to the accelerometer noise (equation 3 and 4), different optical tracking rate will result in only scale factor difference from $76\mu\text{g}$. Table 1 shows the requirements on accelerometer noise when various optical tracking rates are used assuming 5kHz sampling used.

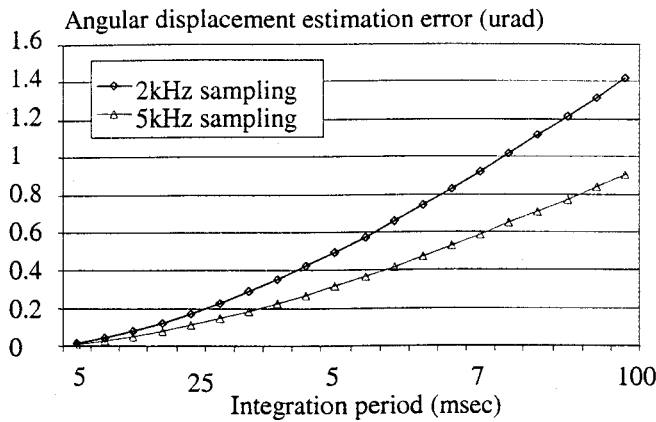


Figure 4. Angular displacement estimation error vs. integration period assuming 0.3m separation of two accelerometers. Acceleration measurement error of $76\mu\text{g}$ was used for two sampling frequencies (2kHz and 5kHz). Notice that higher sampling frequency gives better performance.

rate	10Hz	20Hz	30Hz	50Hz	100Hz
noise	$13\mu\text{g}$	$38\mu\text{g}$	$69\mu\text{g}$	$152\mu\text{g}$	$428\mu\text{g}$

Table 1. Requirements on accelerometer noise for various optical tracking rates.

4. Experiments - concept validation

In this section, our objective is to demonstrate the concept of the accelerometer assisted tracking. To achieve this goal, we took the following steps:

- validation of displacement estimation algorithm
- validation of optimization algorithm for initial velocity error
- integration of (a) and (b) with the tracking/pointing subsystem
- setup of accelerometer and laser beacon on shake table
- operation of accelerometer tracking with various optical tracking rates

Figure 5 shows the setup to demonstrate the accelerometer-assisted tracking concept.

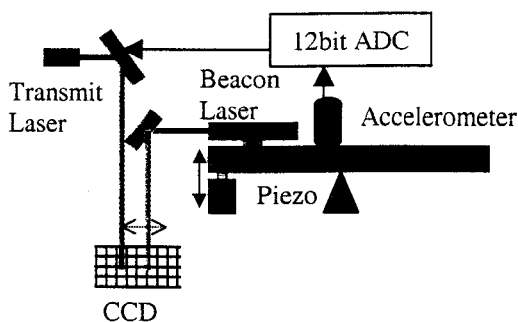


Figure 5. Setup for accelerometer-assisted tracking concept demonstration.

Step (e) of the above validation procedures is worth to explain in detail for concept demonstration. Laser beacon from the shake table was sampled at 1kHz on the CCD and the accelerometer on the shake table was also sampled at 1kHz. The vibration frequency was set to 35Hz and 45 Hz with displacement ranges up to few pixel distances (1 pixel = $45\mu\text{rad}$). In order to establish a reference, only optical tracking was maintained at 1kHz while the beacon centroids and transmit laser centroids were logged to estimate the tracking performance later. Next, accelerometer was used in tracking and optical tracking rate was reduced to 500Hz while maintaining sampling rate of accelerometer constant at 1kHz. The other optical tracking rates were 333Hz, 250Hz, and 200Hz. Figure 6 and 7 show the tracking of sinusoidal motion of beacon at 45Hz with optical tracking only and accelerometer assisted tracking. Table 2 shows rms tracking errors at various optical tracking rates for the two vibration signals.

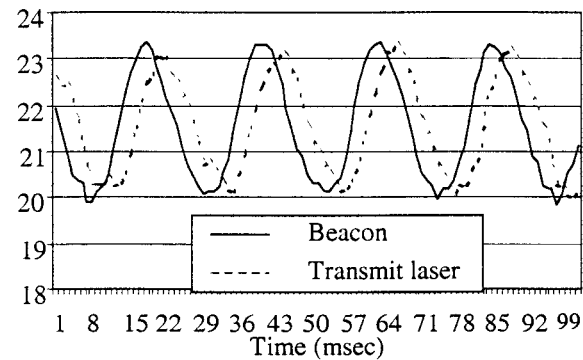


Figure 6. Optical tracking at 1kHz with vibration signal of 45Hz.

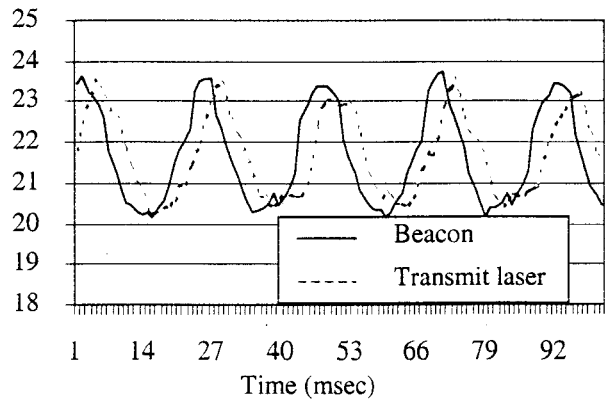


Figure 7. Accelerometer assisted tracking with optical tracking of 200Hz and vibration signal of 45Hz

Vibration of 35Hz

rate	1kHz	500Hz	333Hz	250Hz	200Hz
error	0.77	0.77	0.84	0.90	1.04

Vibration of 45Hz

rate	1kHz	500Hz	333Hz	250Hz	200Hz
error	0.93	0.93	0.95	0.97	0.97

Table 2. RMS tracking errors in pixels for the accelerometer assisted tracking with various optical tracking rates

Figure 6 and 7 clearly show that tracking performance using accelerometer is comparable to that of optical tracking only. This is confirmed in Table 2 where the degradation due to accelerometer is almost negligible for 45Hz vibration. The performance degradation is a function of the vibration signal frequency as is evidenced for 35Hz vibration signal in Table 2 which shows about 25% of gradual increase in error from optical tracking rate of 1kHz to 200Hz. Nevertheless, the results from Figure 6, 7 and Table 2 demonstrates the concept of the accelerometer-assisted tracking is working. The gradual performance degradation was expected due to the displacement estimation error that is a function of random noise coming from accelerometer, building vibration, A/D converter quantization, and other electronic noise. Currently, the total rms random noise using 12bit A/D converter is between 4 to 8mV compared with 76 μ g from QA-3000 accelerometer only. We are working on the upgrades of these hardware to minimize the total random noise level to less than 100 μ g. We believe that this can be achieved as the measured minimum vibration level was reported as 80 μ g.⁶ Once the noise level is reduced, the performance degradation will be small and more predictable as we reduce the optical tracking rates.

5. CONCLUSION

We presented the concept, error analysis, and demonstration of the accelerometer-assisted tracking. This new tracking approach would allow the low intensity beacon signal to be used with accelerometer, which improves the performance pointing subsystem using the available beacon sources such as uplink laser, stars, and Sun-illuminated Earth images. The primary challenge in achieving the desired tracking performance is the minimization of the total random noise in acceleration measurements. Future work includes progressive upgrades of hardware to lower the random noise.

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